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Dr. Jack Kaye
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Dear Jack:

Attached is the final technical report for grant NAGW-3442, 'Observational and Model Studies of Large-Scale Mixing Processes in the Stratosphere'. Please let me know if there is anything further you require, and I will look forward to seeing you at the AMS Middle Atmosphere Meeting in June.

Regards,

Kenneth P. Bowman

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Associate Professor

Final Report NASA Grant NAGW-3442
Observational and Model Studies of Large-Scale Mixing Processes in the Stratosphere

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The following is the final technical report for grant NAGW-3442, 'Observational and Model Studies of Large-Scale Mixing Processes in the Stratosphere'.

Research efforts in the first year concentrated on transport and mixing processes in the polar vortices. Three papers on mixing in the Antarctic were published. The first was a numerical modeling study of wavebreaking and mixing and their relationship to the period of observed stratospheric waves (Bowman 1993a). The second paper presented evidence from TOMS for wavebreaking in the Antarctic (Bowman and Mangus 1993). The third paper used Lagrangian trajectory calculations from analyzed winds to show that there is very little transport into the Antarctic polar vortex prior to the vortex breakdown (Bowman 1993b). Mixing is significantly greater at lower levels. This research helped to confirm theoretical arguments for vortex isolation and data from the Antarctic field experiments that were interpreted as indicating isolation.

A Ph.D. student, Steve Dahlberg, used the trajectory approach to investigate mixing and transport in the Arctic. While the Arctic vortex is much more disturbed than the Antarctic, there still appears to be relatively little transport across the vortex boundary at 450 K prior to the vortex breakdown. The primary reason for the absence of an ozone hole in the Arctic is the earlier warming and breakdown of the vortex compared to the Antarctic, not replenishment of ozone by greater transport. Two papers describing these results have appeared (Dahlberg and Bowman 1994; Dahlberg and Bowman 1995). Steve Dahlberg completed his Ph.D. thesis (Dahlberg and Bowman 1995) and is now teaching in the Physics Department at Concordia College.

We also prepared an analysis of the QBO in SBUV ozone data (Hollandsworth *et al.* 1995).

A numerical study in collaboration with Dr. Ping Chen investigated mixing by barotropic instability, which is the probable origin of the 4-day wave in the upper stratosphere (Bowman and Chen 1994). The important result from this paper is that even in the presence of growing, unstable waves, the mixing barriers around the polar vortex are quite robust.

Research in the latter part of the grant concentrated on understanding the reasons for the existence of the mixing barriers around the polar vortices and the differences between the two hemispheres. By computing Lagrangian trajectories with observed winds that have been filtered to remove waves with particular phase speeds, I have demonstrated very convincingly that mixing in the lower stratosphere is due to Rossby wavebreaking near waves' critical lines(Bowman 1996). Because there are no waves with very fast eastward phase speeds, there is no wavebreaking in the core of the polar night jet where wind speeds are very large. This leads to a region of little mixing and a barrier to isentropic transport. Introducing artificial waves with high phase speeds into the flow causes wavebreaking in the jet core and destroys the transport barrier. A second manuscript in which similar results are demonstrated in the controlled environment of a simple model is in preparation.

We are now completing a study of the tropical mixing barriers that are evident in tracer data. We have used output from the Geophysical Fluid Dynamics Laboratory (GFDL) SKYHI model to investigate the tropical mixing barriers at 450 K. Trajectory calculations show that the tropical barrier mechanism is similar to the one that produces the polar mixing barriers: localized jets have wind speeds greater than the phase speed of the extant waves. In the case of the polar mixing barriers, waves are propagating from a region of low wind speed to a region of high wind speed. As a result, the phase speeds of the waves are slower than the wind speed in the jet. In the case of the tropical barriers, waves are generally propagating from the midlatitudes, where wind speeds are high, into the tropics, where they are low. As a result, they encounter critical lines and break before reaching deep into the tropics. Once again, a zone of weak mixing results from the absence of critical lines and wavebreaking. The tropical barriers in the model are generally more porous than the wintertime polar barriers. Two papers are submitted or in preparation on this subject (Bowman and Hu 1996a; Bowman and Hu 1996b). Mr. Yongyun Hu completed his M.S. thesis in 1996 on this subject.

I have begun a new area of research in large-scale tropospheric tracer transport. The purpose of this research is to develop a theoretical understanding of the mechanisms of tracer transport in the troposphere, with the eventual goal of making quantitative predictions of the behavior of tracers in the atmosphere. The first paper on this subject has been accepted pending revision (Bowman and Cohen 1996). Observations of long-lived tracers indicate that the time required to mix tropospheric air between the northern and southern hemisphere extratropics is on the order of 1 year. Mixing within the extratropical troposphere is known to be quite efficient, with timescales on the order of 1 month, in large part due to effective stirring by Rossby waves and extratropical cyclones. The mechanisms for transport through the tropics, however, are not well understood; and general circulation models have simulated the observed interhemispheric mixing time with varying success. A simple kinematic model of the zonally-symmetric Hadley circulation is developed to investigate whether the seasonal oscillation of the Hadley cells could be responsible for a significant part of the interhemispheric mixing. The simple model captures 78% of the variance in the observed tropical climatological mean-meridional circulation. The flow has two free parameters, α, which defines the strength of the time-mean part of the flow, and β, which defines the strength of seasonal oscillation. Lagrangian trajectories in the model are shown to be chaotic in the formal sense. For observed values of the α and β the mixing time is on the order of 4 months, which suggests that the Hadley circulation alone may account for a large part of the interhemispheric mixing of air through the tropics.

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